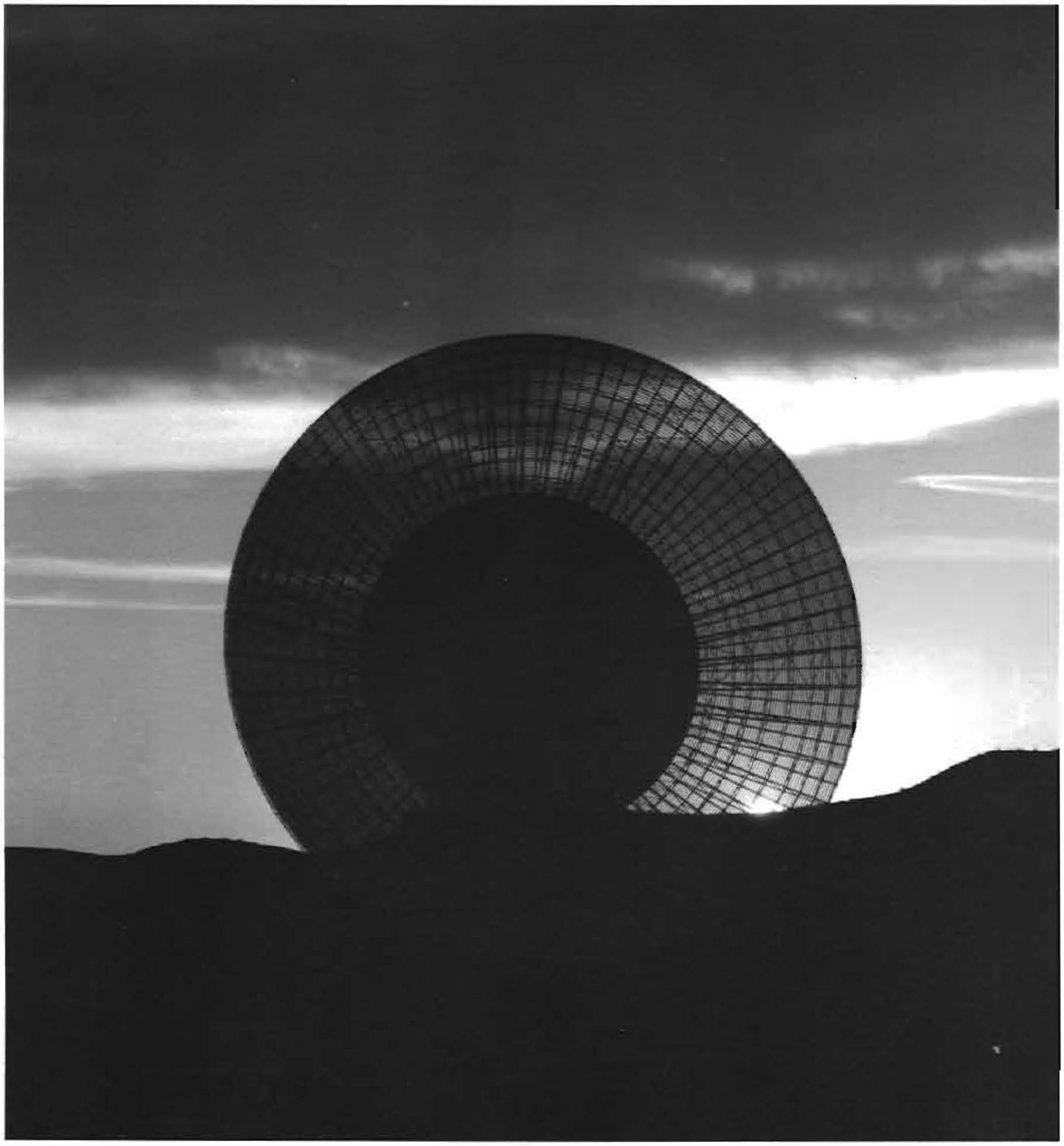
Jet Propulsion Laboratory



1988 ANNUAL REPORT

Cover: The 70-meter-diameter antenna at Goldstone, California

Contents

A description of work accomplished under contract between the California Institute of Technology and the National Aeronautics and Space Administration for the period January 1 through December 31, 1988.

JET PROPULSION LABORATORY
California Institute of Technology
Pasadena, California

Director's Message

1988 was the year that the United States returned to space flight, and this opened the door to a great variety of space science missions planned by NASA for the next decade. JPL spent the year preparing for an April–May 1989 launch of the Magellan spacecraft and an October launch of Galileo. The Laboratory was also busy in 1988 preparing for the August 1989 encounter of the Voyager 2 spacecraft with Neptune. In order to finalize the readiness for the encounter, the Laboratory undertook major tasks both in the ground network and on the spacecraft itself, and testing and calibrating will continue up through the encounter period. It was also a year active with intensive work to combine the science and technology objectives of the CRAF and Cassini missions in preparation for a combined CRAF/Cassini new start. Detailed engineering studies were part of these preparations as well.

The year was also a year of preparation of a different kind. The Laboratory continued to develop advanced technologies that will enable us to undertake a new phase of space exploration. These enabling technologies include advanced microelectronics and remote sensing systems, automation and robotics, and science data visualization. The new phase of solar system exploration will require these technologies for the intensive studies of solar system objects that are planned for the next decade of space research.

But the year found us looking inward as well. We undertook a thorough study of our own projects and capabilties. We examined our prospects for future space exploration missions and determined where our capabilities will be most needed and most effective.

We concluded that we will continue to focus on solar system exploration and be part of any future Mars-intensive program by conducting surface exploration and in-situ experiments; we will continue to develop our capabilities in astrophysics and our ability to seek and study extra-solar planetary systems; and we will continue to prepare ourselves for a principal role in NASA's Earth Observing System.

Institutional interactions and scientific collaborations between the Laboratory and the Caltech Campus solidified further to the benefit of both organizations. As always, the people of JPL remain faithful to their high standards, and their creativity and personal dedication in all aspects of the Laboratory's efforts ensure the continued success of JPL.

So at the end of 1988 we are looking forward to an interesting and, we hope, fruitful period of flight projects, technology development, and exciting scientific results.

Lew Allen
Director

Introduction

The Jet Propulsion Laboratory (JPL) of the California Institute of Technology (Caltech) is a federally funded center that operates under contract to the National Aeronautics and Space Administration (NASA). The people of JPL share a common objective: research and development in the national interest.

Three characteristics shape JPL's philosophy, mission, and goals. (1) As part of Caltech, JPL pursues the highest standards of scientific and engineering achievement. Excellence, objectivity, and integrity are the guiding principles. (2) As NASA's lead center for unmanned exploration of the solar system, JPL has directed unmanned planetary missions for the United States since the space age began. (3) JPL helps the United States solve technological problems and performs research, development, and spaceflight activities for NASA and other agencies.

JPL's primary mission evolved from pioneering rocket research, through guided-missile work, to space missions. Today, JPL is a preeminent national laboratory with a budget of about $1 billion and a workforce of 5,736 people. Its charter continues to be the exploration of the solar system. This includes participation in the observation of planet Earth, as NASA recently awarded JPL a prominent role in the development of the Earth Observing System (Eos), a series of orbiting scientific platforms that will study our planet.

Thus, JPL's challenge is twofold: to explore the solar system and to begin the very necessary observation of Earth in order to understand global change and assure a safe environment. To achieve these goals, JPL scientists and engineers are developing advanced remote-sensing systems, exciting new information and data-system architectures, multidimensional scientific data visualization and integration techniques, space computer hardware including supercomputer applications and microelectronic devices, and more. Other areas, such as machine intelligence and robotics, are being developed for both NASA and defense sponsors.

In 1988, the year reported here, there was renewed excitement as NASA returned to space with the flight of the shuttle Discovery between September 29 and October 3. Immediately, NASA went forward with its backlogged launch manifest, which in 1989 will include two JPL missions: Magellan to Venus in April and Galileo to Jupiter in October. The discovery begins again.

Flight Projects

Scientific and engineering teams spent the year working toward the fast-approaching launches of two important spacecraft. Magellan, the mission to map Venus at high resolution, will depart in April, the first JPL planetary spacecraft launched since Voyager 1 on September 5, 1977. Galileo, a combined orbiter and atmospheric probe, will follow in October Galileo will tour a large part of the solar system en route to Jupiter. Once there in late 1995, the probe will sample the Jovian atmosphere, and the orbiter will study the planet, its satellites, and its magnetic environment for 20 months. Two other spacecraft, Mars Observer and Ulysses, will be launched in the opening years of the next decade.

Teams also went forward with plans for future flight projects, such as the Comet Rendezvous Asteroid Flyby and Cassini (CRAF/Cassini) mission. The two spacecraft have a common heritage: the Mariner Mark II design. Comet Rendezvous Asteroid Flyby will study asteroids and a comet at close range. Cassini will orbit Saturn, sampling its atmosphere and observing the surface of its largest satellite, Titan. A joint study with the Johnson Space Center of a Mars Rover Sample Return mission also continued. Interest in the project is high since it would gather and return samples to Earth, as well as obtain information needed for subsequent manned missions.

Meanwhile, Voyager continues as the longest-running and most spectacular flight project to date. Voyager 2 will make its final encounter—with Neptune and its fascinating satellite, Triton—in August 1989.

Voyager

The Voyager team continued preparations for Voyager 2's closest encounter with Neptune on August 25, 1989, 12 years and 5 days after launch and 8 years after its primary mission to Jupiter and Saturn was completed. Voyager 2 will make its closest approach to Neptune at 9 p.m. (PDT) on August 24, but because one-way light-travel time from Neptune is 4 hours and 6 minutes, signals from Voyager's closest approach will not reach Earth until 1:06 a.m. (PDT) on August 25.

Project personnel are developing computer programs for the Neptune encounter, which will begin in June and run through September. All sequences except that for closest approach are complete and ready to be updated next spring, based on the latest pointing and timing information and on discoveries by Voyager and Earth-based observers.

Light at Neptune will be about half what it was at Uranus, because Neptune is so much farther from the Sun. Still, Voyager 2 may take as many as 24,000 photographs of Neptune's environs. The relative darkness will require new techniques to gather those pictures. Software is being modified to allow longer exposure times for the cameras. Image-motion compensation, in which the spacecraft turns slowly to track its photographic target, will help produce sharp, clear pictures because camera shutters can stay open longer.

Normally, the great distance between Neptune and Earth would force engineers to slow the rates at which Voyager 2 sends its data. But modifications to Voyager's software and to the ground system will bring nearly as much scientific data at Neptune as at Uranus.

The Deep Space Network's (DSN) 64-meter antennas have been enlarged to 70-meter diameter. As they were for Uranus, the antennas will be arrayed with those from other organizations to help capture data. The 64-meter Parkes radio-astronomy antenna in Australia will work in concert with the DSN Canberra stations. All 27 of the 25-meter antennas at the Very Large Array in Socorro, New Mexico, will team with the DSN Goldstone station. A 64-meter antenna at Usuda, Japan, will help with radio-science measurements during Voyager's closest approach to Neptune.

Magellan

After launch aboard the space shuttle in April, Magellan will proceed to Venus and conduct the most comprehensive observation of its surface and gravitational features ever undertaken.

Past Soviet Venera photographs showed tiny patches of the surface of Venus and hinted at fine-grained dust and small rocks. Low-resolution radar from NASA's Pioneer Venus orbiter hinted at great volcanoes, continents, plains, and ocean basins. However, since thick, dense clouds shroud the Venus surface, good maps of the planet that used to be called Earth's twin were not possible until Magellan.

The project spent a busy year. The spacecraft was completed at Martin Marietta in Denver, and the radar at Hughes Aircraft; they were both shipped to Kennedy Space Center (KSC), where Magellan is being prepared for launch.

At Kennedy Space Center, a minor fire broke out when a technician accidentally made a wrong electrical connection. An investigation board found no serious damage; new procedures were instituted to prevent any such future occurrence, and preparations for the April launch were resumed.

Galileo

Jupiter has fascinated scientists since Galileo Galilei first trained his telescope on the planet 378 years ago. The Galileo mission includes a combined orbiter and atmospheric probe that will delve deep into the mysteries of the gases that make up the planet and study the satellites,

magnetic environment, and the planet itself for at least 20 months.

The spacecraft will be shipped to Kennedy Space Center at midyear. Plans focus on a launch opportunity that begins on October 8, 1989, and extends for more than a month.

In the shuttle, Galileo will sit atop an inertial upper stage that will propel it from Earth orbit. Because the upper stage does not have the energy to send the spacecraft straight to Jupiter, Galileo will fly a gravity-assisted path—once past Venus then twice past Earth. Jupiter will come into view in late 1995, when the primary mission will begin.

After being reworked for the high temperatures it will encounter in the inner solar system, Galileo was reassembled and tested in 1988. The mission's science objectives, augmented for the new trajectory, now include observations of Venus, Earth, the Moon (Galileo will photograph its north pole, which has not been mapped), and the asteroids Ida and Gaspra, as well as the full complement of investigations within the Jovian system.

Mars Observer

Scientists have shown great interest in a return to Mars—many unanswered questions still remain concerning the water of Mars, possible past conditions supportive of early life, and the plate movement of the planet. The Mars Observer Project will provide many of the answers to these questions.

The project continued moving toward a 1992 launch. The spacecraft will spend a Martian year (almost two Earth years) studying the chemistry of Martian soil and the planet's climate from orbit.

Late in the year, the United States and the Soviet Union agreed that the Soviets should place an instrument aboard Mars Observer. The plan was part of an agreement between the two countries to share data on the exploration of Mars.

The spacecraft, originally to have been launched by the space shuttle, will now fly on a Titan 3 and a Transfer Orbit Stage—a new commercial upper stage.

Ulysses

Ulysses, a cooperative mission between NASA and the European Space Agency, will explore both poles of the Sun and interstellar space near the Sun's polar regions. Ulysses will be launched in October 1990 aboard a shuttle–inertial-upper-stage combination. After the shuttle boosts Ulysses into Earth orbit, the inertial upper stage and a small, solid-propellant motor will drive the spacecraft onto its gravity-assisted path.

The spacecraft, which was provided by the European Space Agency, is now stored in Germany. Science instruments are at the principal investigators' facilities. Instruments and spacecraft will come together next year and final tests will begin.

TOPEX/POSEIDON

The Earth is a planet, too. Spacecraft can give entirely new and fascinating perspectives to students of our home planet, especially of ocean areas and regions not otherwise easily accessible.

So NASA and the French space agency, the Centre National d'Etudes Spatiales, are cooperating on an Earth-orbital mission to study sea levels and ocean currents using radar altimetry. The spacecraft, built by Fairchild Space Company, is managed by JPL. The Ocean Topography Experiment (TOPEX)/POSEIDON will be launched in December 1991 on an Ariane rocket from Kourou, French Guiana; it will move into an 830-mile-high orbit inclined 63 degrees from the equator.

NASA Scatterometer

JPL also has a major role in another oceanography project, the NASA Scatterometer. The scatterometer project is developing a backscatter radar and a ground-data processing system to make frequent, high-resolution measurements of wind

speed and direction near the ocean's surface. From polar orbit, the scatterometer will see 90 percent of the ice-free oceans every two days. To assist research, the ground-data processing system will pass information on winds to oceanographers and meteorologists for three years.

In April, after project managers proposed it, NASA agreed to fly the scatterometer on Japan's Advanced Earth Observing Satellite. The Japanese planned to select instruments near the end of 1988; their initial reaction to the scatterometer proposal was favorable.

Throughout the year, work continued on design of the instrument. Subsystems are being built. The antennas were delivered to JPL, and breadboards of the radio-frequency and computer electronics are complete. Development of algorithms to process data on the ground is nearly complete.

CRAF/Cassini

The Comet Rendezvous Asteroid Flyby/Cassini (CRAF/Cassini) project will be NASA's next solar system exploration effort and will be launched by Titan IV/Centaurs. The two missions will share the common heritage of the Mariner Mark II spacecraft.

The CRAF mission will study asteroids and a comet for clues to sources of primordial elements, the evolution of our solar system, and the origins of prelife materials. Meanwhile, Cassini will orbit Saturn and place a probe into the atmosphere of its large and fascinating satellite Titan.

The year's major effort has been the evolution of a common spacecraft design. Only the science instruments are different. The Federal Republic of Germany will provide the comet spacecraft's propulsion module. Cassini's propulsion module will be of the same design. The project is expected to start in fiscal year 1990. NASA selected 13 instruments for the comet flight.

Mars Rover Sample Return

The United States has shown interest in yet another return to Mars—this time with astronauts. The undertaking, possible sometime in the next century, would require a number of unmanned precursor flights of the planet.

One such precursor to the manned flights might be the Mars Rover Sample Return project. JPL continued to study this project, which would bring samples of the Martian soil, rock, and atmosphere back to Earth. If the study reaches project status, it would start in 1993 and launch in 1998. The potential for international cooperation is high.

The current study phase is divided into functionally discrete segments: a surface rover, a Mars ascent vehicle, a mapping and communications orbiter, a sample-return orbiter, and a geophysical/meteorological station. JPL is responsible in this study phase for overall study management, mission design and system engineering, the surface rover, and the mapping/communications orbiter.

Space Station Freedom

JPL is assessing scientific activities in NASA's new space station, Freedom. The station, to be assembled in orbit beginning in 1995, will extend human presence into near space. The station will provide the base for a broad spectrum of ambitious instruments: a telescope to look for planets around other stars, radars to peer into the complex environment of the tropical atmosphere, and new experiments to capitalize on the special conditions of microgravity.

Earth Observations

Earth should be viewed as a system, an evolving planet. The realization that our home is a unit is relatively recent. NASA is undertaking a new Earth Observing System (Eos) that aims to

bring to all humans a better understanding of the environment in which they live.

The Earth Observing System will be the largest and most significant Earth-science project NASA has attempted. It will provide long-term observations of this planet and a supporting information system so that people can observe, analyze, and understand how Earth functions as a natural system.

The system is a coordinated theoretical and observational effort to study Earth's processes, from the upper atmosphere to the depths of the ocean. Eos will study carbon dioxide, ozone, and other active trace gases produced by humans; seasonal and annual weather events; and even anomalies like El Niño. As scientists in the United States and the rest of the world prepare for the Earth Observing System in the mid-1990s, JPL scientists and engineers are planning to study climate processes with instruments to measure changes in many of the Earth's variables.

As part of the program, the United States plans to develop two large, polar-orbiting platforms. This year JPL and Goddard Space Flight Center (GSFC) were assigned responsibility for important, complementary elements of the mission. JPL will be involved in the development of the Polar-Orbiting Platform 2 and will be responsible for three major facility instruments, as described below for Eos Platform 1: the Atmospheric Infrared Sounder (AIRS), the High-Resolution Imaging Spectrometer (HIRIS), and the Synthetic-Aperture Radar (SAR).

Atmospheric Infrared Sounder

The Earth Observing System will study global change. To accomplish this, scientists need an accurate, long-term set of observational data, some of which do not exist today. NASA has chosen JPL to develop and operate a new instrument to fly in Earth orbit. The new Atmospheric Infrared Sounder (AIRS) will provide more accurate data about the atmosphere, land, and oceans for application to climate studies.

The instrument, whose heart is a grating spectrometer that will use cooled detectors, will provide day and night global coverage of Earth twice every 24 hours. The sounder will simultaneously measure outgoing infrared radiation between 3 and 17 micrometers in 4,000 high-spectral-resolution channels.

AIRS will make global measurements of the following: atmospheric temperature profiles (accurate to 1 degree Celsius), relative-humidity profiles and precipitable water vapor, fractional cloud cover, cloud-top pressure and temperature, total ozone burden of the atmosphere, distribution of minor gases such as methane, carbon monoxide, and nitrous oxide, sea-surface temperature (again, accurate to 1 degree Celsius), land temperature and infrared emissivity, surface brightness, snow and ice cover, outgoing long-wave radiation, and the precipitation index. These data will make major contributions to understanding the increased greenhouse effect, the global energy and water cycles, atmosphere-surface interactions, numerical weather prediction, and climate changes and trends.

High-Resolution Imaging Spectrometer

Because so much information is invisible to the human eye, scientists are taking advantage of advancements in infrared technology to see things they could never see before.

For instance, JPL has developed short-wavelength infrared detector arrays for the High-Resolution Imaging Spectrometer (HIRIS), part of the Earth Observing System. These sensors will be used in ground- and space-based instruments.

One new detector has been built into the Area Array Camera, an infrared instrument that will be used on the 24-inch telescope at Table Mountain Observatory to take infrared images of planets, comets, and other astronomical objects. Scientists will use the images to map planetary mineralogy and the distribution and characteristics of dust and other particulates in the Earth atmosphere.

Synthetic-Aperture Radars (SARs)

The Shuttle Imaging Radar-C (SIR-C) science team will provide a deeper understanding of how radar measures soil moisture and precipitation and monitors changes in forests and wetlands. The team will also establish the paleoclimatic history of Earth's arid regions.

The radar science team, selected in July, includes 49 team members and three associates. They will perform experiments that span the range of Earth-science disciplines using an L- and C-band imaging radar polarimeter being built by JPL and an X-band radar that will be provided by Germany and Italy.

The knowledge generated by this effort is vital in understanding how the Synthetic-Aperture Radar on the Earth Observing System can identify global change. Results and experience will be applied to the development of the Eos SAR instrument.

Atmospheric Trace Molecule Spectroscopy

The Atmospheric Trace Molecule Spectroscopy experiment (ATMOS), a shuttle-borne instrument that detects and monitors gases in the atmosphere over the entire globe, is one of the JPL instruments that has made significant contributions to a new understanding of events occurring in Earth's atmosphere. ATMOS flew in 1985 on Spacelab-3 and took 2,000 high-resolution spectra of the upper atmosphere.

During the hiatus in shuttle flights from January 1986 to September 1988, the ATMOS instrument monitored the atmosphere from Table Mountain Observatory, looking for changes in composition and stability. While a sister experiment, Mark IV, flies over the poles on NASA's DC-8 research aircraft to study ozone depletion, ATMOS has conducted similar studies from the ground at McMurdo Station in Antarctica. The ATMOS instrument will fly a series of special new shuttle missions that will start in December 1990 and continue about once a year into the next century.

Microwave Limb Sounder

Interest in Earth's atmosphere has intensified as scientists have begun to understand the effects of pollution and other human activities. One instrument that should make a major contribution to study in this area is JPL's Microwave Limb Sounder (MLS), destined to fly on the Upper Atmosphere Research Satellite (UARS).

The protoflight model of the MLS has been assembled and is being tested in the Spacecraft Assembly Facility at JPL. Preliminary results indicate that the instrument will perform as expected. The power supply and spectrometer assemblies have already passed vibration testing. Delivery of the instrument to the integration contractor is scheduled for early October 1989.

Geodynamics Program

The JPL Geodynamics Program looks at variations in the position of Earth's spin axis, the length of the day, and motions and deformations of Earth's crust by using Very Long Baseline Interferometry (VLBI), ground-based laser ranging, and Global Positioning System (GPS) satellites. Studies of Earth's atmosphere and the length of the day reveal that atmospheric effects dominate variations in rotation with periods of a year or less. Fluctuations with periods of tens of years are attributed to interactions between Earth's core and mantle.

JPL is leading NASA's efforts to develop a geodetic system to study crustal motion based on the GPS. Seven GPS satellites are now operating and 24 will be in 12-hour orbits by 1992. Receivers have been designed to track and process their signals so that engineers can pinpoint each receiver antenna. Monitoring the Earth's shifting tectonic plates involves measurements by antenna networks that span the boundaries between Earth's great crustal plates, using baselines up to thousands of kilometers long. Gathered over several years, the data should allow scientists to determine relative velocities of the plates—between 0 and 20 centimeters a year. JPL's geodesy system can

measure changes as small as 1 centimeter on baselines up to 2,000 kilometers.

In January, JPL led a geodetic experiment in Central and South America that involved the network of satellites. Investigators from 13 countries and 30 international agencies and institutions placed receivers in Colombia, Venezuela, Panama, Costa Rica, and Ecuador, and on islands in the Pacific Ocean and the Caribbean Sea. The experiment studied tectonic motion in a region where five of the plates interact. Yearly field campaigns will collect data from 1990 to 1995 and should result in better comprehension of the plates' movements.

JPL is also designing an advanced receiver for the Global Positioning System. In January, two prototype receivers about 250 kilometers apart collected data that included range measurements of unprecedented accuracy. In May, the receivers flew aboard an airplane that tracked the satellites and provided information on the airplane's position and attitude.

Astrophysics

Wide-Field/Planetary Camera

The most distant reaches of the universe have never been seen, nor is the age or fate of the universe known. A new instrument, the Wide-Field/Planetary Camera, may provide new insights. The Wide-Field/Planetary Camera, built by JPL and Caltech Campus, is the primary scientific instrument on the Hubble Space Telescope. The camera will use charge-coupled devices to record images of some of the most distant objects in the universe. Launch of the Hubble Space Telescope was initially set for summer 1989, but was then delayed until February 1990. However, when the shuttle manifest changed after Discovery flew successfully in September, telescope engineers and astronomers were told to be ready for launch in December 1989.

Hubble Imaging Michelson Spectrometer

The Hubble Space Telescope could become a permanent astronomical facility in Earth orbit, above the polluting atmosphere. New instruments of many kinds are being designed as second-generation experiments.

The Hubble Imaging Michelson Spectrometer is a joint JPL effort with the University of Hawaii Institute for Astronomy to develop a second-generation infrared instrument for the Hubble Space Telescope in the mid-1990s. JPL is developing improved detectors as part of the activity. The first of the new detectors was installed last summer on the Hawaiian Institute for Astronomy's 2.2-meter telescope on Mauna Kea. Next year, scientists will use even more powerful detectors with a much larger field of view.

Michelson Stellar Interferometry

Albert A. Michelson invented interferometers, earning the first Nobel Prize in physics for an American scientist. Interferometers are still widely used because of their incredible sensitivity.

Now, engineers at JPL have built two Michelson stellar interferometers—one for measuring the positions of stars and the other for high-resolution imaging. JPL is also studying the feasibility of putting a long-baseline interferometer on the space station. Optical interferometry, which Michelson used at Mount Wilson in 1930, allows the imaging of sky objects at resolutions 10 to 100 times better than the largest optical telescopes.

Life in the Universe

"Is there other life in the universe?" is almost as intriguing a question as "Where did life come from?" JPL has roles in attempts to answer both questions.

In 1988, JPL significantly expanded studies of techniques to detect neighboring solar systems as part of NASA's Life in the Universe program. Three major tasks are under way:

- Construction of a Circumstellar Imaging Telescope that would fly on the space shuttle. An occulting disc inside the telescope blocks the path of light from the central star and allows astronomers to see any cool material surrounding the star.
- Construction of an astrometric telescope that will measure a star's wobble as a planet orbits it.
- Development of wide-baseline interferometric techniques, which will allow high-resolution imaging.

Those techniques are designed to detect any planets that may be circling other stars; no assumptions are made about life on such planets. This is the task of the Search for Extraterrestrial Intelligence (SETI), which will scan the sky with large radio antennas to listen for signals from intelligent species elsewhere in the universe.

In 1988, the Microwave Observation Project, part of the search for extraterrestrial intelligence, began at JPL and NASA's Ames Research Center (ARC). The long-term schedule calls for the search to begin at the DSN Venus Station at Goldstone in October of the International Space Year, 1992.

Flight Projects Support

The Flight Projects Support Office (FPSO) role remains to support ongoing missions and develop new information systems. In addition, FPSO is developing tools that will help track budgets and tasks and develop stronger correlations between resources, commitments, and schedules.

Preparations for the Magellan mission occupied a large part of the office's time this year. Magellan moved into the first part of the new mission support area in the Space Flight Operations Facility (SFOF) and received the first of its Space Flight Operations Center (SFOC) hardware. Major modifications were made to the Mission Control and Computing Center (MCCC).

Space Flight Operations Center

The Space Flight Operations Center (SFOC) is a multimission ground-data system that is replacing the existing Mission Control and Computing Center (MCCC) with state-of-the-art technology. The new system uses the latest technology in information systems, including user workstations, local-area networks, and centralized database management systems. Phase One is composed of more than 400,000 lines of executable code and more than 50 computers networked together. In the future, the center will grow to more than one million lines of code and hundreds of computers.

Magellan will be the first flight project to use the new system. Galileo, Voyager, Mars Observer, Ulysses, and CRAF/Cassini will use it later. By 1992, the Mission Control and Computing Center will be retired.

A Data System for Autonomous Exploration

Vehicles for planetary exploration and remote Earth-sensing must carry many complex instruments that collect data at several hundred wavelengths. The data are for geological and atmospheric surveys. Someday, they may help scientists choose paths for a planetary rover that will take rock and soil samples.

Currently, however, the limitations of most existing spacecraft transmitters allow only a fraction of the data to be sent back to Earth; existing techniques allow an even smaller amount to be analyzed in real time. To achieve the best results from an exploratory mission, data must be analyzed in real time so that machines can make autonomous decisions.

JPL is developing a system for autonomous, real-time, high-dimensional image-data reduction and information extraction. This system must collect data from multiple sensors and then decide, based on incoming data and scientific objectives, how instruments will be configured and resources allocated. Such a system will not need human operators. It will examine an image, classify the geological spectra in the picture, make its own decisions, and reduce massive amounts of data to a compact form.

Space and Earth Science

New information and knowledge are the ultimate aim of all activities at the Jet Propulsion Laboratory. This year's work in 1988 brought a new understanding of Earth, other planets in our solar system, and interstellar space.

The Clouds of Neptune

Every time a spacecraft nears a new planetary target, astronomers over the world take to their telescopes. With the instruments that can be attached to those telescopes today, the scientists can often see or at least get a hint of phenomena that spacecraft science teams should watch for. Just before the Voyager arrivals, such ground-based observations were made of Jupiter, then Saturn, and finally, Uranus. The results were worth the effort: Astronomers predicted volcanoes on Io, storms in the clouds of Saturn, and the rings of Uranus.

To prepare for Voyager 2's last encounter, astronomers from JPL have been studying Neptune with telescopes and cameras. Unlike the clouds at Uranus, which the spacecraft passed in 1986, Neptune's clouds can be seen from Earth. Methane in Neptune's atmosphere causes the planet to appear dark when observed through some methane filters. But high in the atmosphere, clouds reflect sunlight before it penetrates deep enough to be absorbed. The high clouds appear brighter than the rest of the planet. In the past, clouds had been seen only in images at a strong methane band. However, images taken by a JPL astronomer at Mauna Kea Observatory in 1988 showed clouds in a weak methane band.

Astronomers can calculate a planet's rotation rate by tracking the clouds' apparent motion as the planet turns. In the past, astronomers had calculated the rotation period of Neptune's atmosphere at 17 hours by measuring the brightest visible cloud at 40 degrees south latitude. The brightest feature visible in the new pictures at 30 degrees south latitude, however, rotated in 17.7 hours. The different speeds indicate a wind shear of about 170 meters a second, comparable to strong changes in wind direction found on the other giant planets.

When Voyager draws closer to Neptune (after April), the wide-angle camera should show clouds and a polar haze. Voyager's better resolution will complement the Earth-based observations.

Emission from Jupiter and the Solar Wind

Particles traveling near the speed of light stream from Jupiter's magnetosphere, and the rate at which it happens depends on sources and losses of high-energy electrons in the planet's equivalent of the Van Allen radiation belts.

Scientists at JPL had hoped to see if variations in the synchrotron emission have any correlation with the solar wind. Using solar-wind data from spacecraft near Earth, the scientists found significant correlation that appears to be associated with solar-wind ram pressure, ion density, thermal pressure, flow velocity, momentum, and ion temperature. Their study implies that the solar wind influences the numbers of electrons in Jupiter's inner magnetosphere.

Studies of the Ozone Layer

During the past two years, the serious nature of environmental damage to Earth was driven home in dramatic fashion: A hole in the Earth's protective ozone layer above Antarctica is related to the release of man-made chemicals called chlorofluorocarbons into the air. The drought and heat that hit much of the United States in the summer was seen as advance warning that the atmosphere is overloaded with carbon dioxide. Scientists and governments need to understand the causes and implications of such climate anomalies.

British scientists discovered the depletion in the ozone layer three years ago. It has reappeared each southern spring. JPL scientists joined the studies and have made key contributions to research in the field. Apparently, the chlorofluorocarbons reach the stratosphere, where they break down and release chlorine, which adheres to ice crystals. In complicated chemical processes, the chlorine, along with ultraviolet radiation from the Sun, breaks down the ozone molecules into single oxygen atoms. One surprising finding was that lower-altitude weather plays a part in the process over Antarctica.

Mountain waves over Antarctica were the unexpected discovery by a JPL group participating in the Airborne Antarctic Ozone Experiment. A Microwave Temperature Profiler, the only airborne instrument that measures air temperatures at altitudes above and below its own position, flew on NASA's high-altitude ER-2 aircraft in August and September 1987. Scientists analyzed the data recently and found more than a dozen up-and-down waves that seem to be caused by air flowing over the mountains below. These waves produced the ice clouds that are such a key part of the complicated events that lead to ozone depletion by chlorine. Large ice particles are believed to fall out, taking with them nitrogen compounds and water. This may explain the denitrification process that is known to occur and that is crucial to explanations of why the Antarctic ozone hole forms each year. If mountain waves contribute to the ozone hole, they might account for changes in the severity of ozone loss from year to year, since some years have more weather that favors mountain-wave generation than others. Scientists believe that mountain waves are less frequent in the Arctic, which may help to account for smaller losses of ozone over the north pole.

The Upper Atmospheric Research Program at JPL continues to study Earth's ozone layer to determine the extent to which human activities and natural processes deplete that thin, protective shell in the upper atmosphere. The program includes both field measurements and laboratory studies, the former conducted by instruments on balloons, aircraft, and the ground. In 1988, JPL scientists flew three flights with giant Mylar bags launched from Palestine, Texas, and Fort Sumner, New Mexico.

In two flights from Palestine, a Balloon-borne Laser In-situ Sensor measured how nitrogen, hydrogen, and chlorine compounds affect photochemistry at the high altitudes of the stratosphere and also compared infrared measurements with those taken from a new ultraviolet photometer on the gondola. Both instruments measured the upper limits of hydrogen peroxide, hypochlorous acid, methane, water vapor, and nitrous oxide. Another version of the instrument, for use in airplanes, is being prepared for NASA's Antarctic campaigns.

Launched from Fort Sumner, a Balloon Microwave Limb Sounder measured ozone and chlorine monoxide in the stratosphere. Chlorine monoxide apparently plays the most important role in the depletion of the ozone layer. Meanwhile, the JPL Ozone Lidar instrument, mentioned in the 1987 annual report, began long-term monitoring of stratospheric ozone at JPL's Table Mountain Observatory. Lidar, the laser equivalent of radar, can probe as high as 100 kilometers into the stratosphere. The instrument transmits laser pulses and makes a profile of the concentrations of ozone. Data are being acquired year-round to observe small, man-made trends that underlie large natural variations in the ozone. Seven months of research show that in winter, the upper stratosphere is unstable, and amounts of ozone vary rapidly. Later on in the summer, fluctuations in the amount of ozone diminish and the amount of ozone increases.

Laboratory studies at JPL, meanwhile, concentrated on those photochemical processes that are unique to the Antarctic stratosphere: chemical reactions on ice crystals and reactions of chlorine monoxide.

Mapping Water Vapor in the Atmosphere

Earth's atmosphere contains a great deal of water vapor, an important component in the hydrologic cycle. The heat stored in the water vapor is a significant factor in the atmosphere's energy budget. The vapor complicates attempts to analyze surface materials, the most important of which are vegetation, soil moisture, and surface minerals. Knowledge of the abundance of water vapor in the atmosphere should help to separate atmospheric and surface components, but estimating evaporation from the surface—both sea and land—is difficult.

An Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), built and flown by JPL, may help to solve the estimation problem. The instrument most easily sees water vapor, but also measures gases such as ozone, oxygen, and carbon dioxide. AVIRIS has detected water distribution with high abundance at low elevations and low abundance at high elevations; this corresponds to the expected distribution in the atmosphere. Deviations that mirror topography may show the horizontal movement of water vapor and local sources or sinks, either in the atmosphere or on the surface.

Remote Sensing of Active Volcanoes

Volcanism is one of the most powerful and important processes on Earth. Eruptions can affect weather and climate and can be devastating in terms of lives lost or property destroyed. Unpredictable and dangerous, particularly when they emit ash, lava, and poisonous gases, volcanoes have been difficult to study, and data on their basic physical processes are rare.

During a recent flight of the NASA C-130 land-survey aircraft to Hawaii, JPL's volcanology team observed a hot-water plume emanating from the ocean outlet of the active lava tube system at the Kalapana (new) vent of the Kilauea volcano. To the team's knowledge, it was the first time that a lava-into-ocean discharge point has been monitored with high-sensitivity, thermal-infrared imaging spectrometers.

With volcanologists from the United States Geological Survey's Hawaii Volcanoes Observatory, the JPL team collected data during day and night flights using a Thermal Infrared Multispectral Scanner and Thematic Mapper simulator scanner to map fractures and other high-temperature sources in the lava. The hot-water plume, caused by incandescent lava falling directly into the sea, could be seen clearly in the data, extending several kilometers offshore. High ocean temperatures extended several kilometers directly offshore from the lava outlet, and water temperatures were elevated several kilometers downstream.

Observations of Supernova 1987A

Supernovas, such as the one discovered early last year in the Large Magellanic Cloud, are believed to synthesize heavier elements such as radioactive isotopes. An important element is nickel-56, which decays via cobalt to iron and produces gamma rays.

This year, JPL scientists analyzed gamma radiation seen by a balloon-borne JPL spectrometer launched from Alice Springs, Australia, and found the characteristic signature of cobalt from the supernova. The observations placed major constraints on the dynamics of the star's explosion, revealing a nickel-56 presence equal to about seven percent of the Sun's mass. These data are important, since supernovas are so rare that scientists must usually depend on theoretical calculations alone to determine what happens not only during the death throes of stars, but also during the spread of the resulting matter across the universe. The gamma-ray line, for example, tells about the distribution of radioactive cobalt in the remnant of the star, its velocity and turbulence, and the structure of the outer layers of the supernova's expanding material.

Infrared Processing and Analysis Center

The Infrared Processing and Analysis Center (IPAC) was set up on Caltech Campus to increase the scientific return from the Infrared Astronomical Satellite (IRAS), the first all-sky infrared survey from space. Scientists and engineers at the

center continue to learn more about the data and to produce better data for astronomers. This year, the center began to collect all available data on extragalactic objects and to organize it into a database accessible to any astronomer. When fully operational in 1989, the database will become a powerful research tool for scientists specializing in extragalactic studies.

Scientific Data Visualization

The human eye has an enormous capacity to observe large amounts of displayed data and to retain information about observed correlation and anomalies. Scientific data visualization allows the display of such data in a manner suitable for scientific analyses. The techniques involved will help scientists cope with and manage the flood of digital data that future spacecraft will soon be sending back to Earth.

Several research projects benefit from JPL's leadership role. A Meteorological Parameter Extraction From Satellite task uses visualization techniques to perform three-dimensional analyses of Earth's atmosphere and determine the relationships between clouds, air temperature, and topography. A simulated flight over the surface of the Uranus satellite Miranda (Miranda: The Movie) gave scientists a close look at the topography from Voyager 2 images. A similar task (Mars: The Movie) is under way for Mars. The latest scientific animation production (Earth: The Movie) is a three-dimensional, whirlwind tour of the Earth that flies over, under, and through cloudtops. The film shows cloud cover from December 31, 1978, to February 4, 1979.

Advanced Technology

Wherever we look around us, advances in technology demand our attention—from the computer chips that control how our automobiles function to the intriguing new ways of getting more pictures back from Voyager 2 at Neptune. Advanced technology allows us to do today what was impossible yesterday.

Receiving images from distant spacecraft is an example of advancing technology. When Mariner 4 took the first photos of Mars back in 1965, it was able to send 21 pictures, all black-and-white, at 8-1/3 bits per second. In a historical sense, it was but the blink of an eye before JPL was receiving 35,000 color and black-and-white images of Jupiter from the Voyagers at 116,000 bits per second. In 1965, it took hours to build a single image; in 1979, it took only minutes. Another example of advancing technology is the speed with which computers here on Earth can process the data that make up those pictures. When JPL computer scientists made the computer film of Uranus' satellite Miranda, they spent months on the project. By the time Voyager 2 reaches Neptune, the Caltech Campus–JPL Hypercube will be able to process data from Triton in near-real time.

The advanced technology projects of JPL receive special attention: discretionary funds, recruiting efforts, and new facilities. Each project is overseen by a leader who coordinates technical efforts, fund raising, and facilities planning.

Among the technology thrusts pursued at JPL are space microelectronics, automation, and robotics. The year 1988 saw many accomplishments both within and outside these thrust areas.

Technology Thrusts

The Center for Space Microelectronics Technology

The organization known as the Center for Space Microelectronics Technology (CSMT) came into being on January 21, 1987, to address NASA and Defense Department space programs. The center conducts research and development in solid-state devices, photonics, custom microcircuits, and computer architectures. Guidance is provided by a Board of Governors consisting of senior management in NASA, the Strategic Defense Initiative Organization (SDIO), the Defense Advanced Research Projects Agency (DARPA), Caltech Campus, and JPL. Caltech faculty also take a strong interest in the center.

The CSMT manages the Microdevices Laboratory (MDL), which was dedicated on October 27. The MDL is a 38,000-square-foot, three-story building with clean rooms, laboratories, and offices for 60 people. It will be equipped with $12 million worth of state-of-the-art fabrication and measurement equipment and will allow the end-to-end fabrication of devices based on silicon, gallium arsenide, and other exotic semiconductor materials.

Solid-State Devices

A state-of-the-art electron beam lithography system that can pattern photoresistors with features smaller than 100 angstroms has been acquired for the Microdevices Laboratory. The system will provide tremendous impetus to conduct research on ultrasmall devices.

The laboratory will also be equipped with three molecular-beam epitaxy (MBE) machines. One will be new and the others are being moved from other JPL facilities. Molecular-beam epitaxy permits the fabrication of atomically smooth and abrupt layers and interfaces. By varying composition and thickness of the layer, unique electronic and optoelectronic properties that cannot be obtained in naturally occurring crystalline materials may be engineered.

Photonics

The Center for Space Microelectronics Technology is developing photonic materials, devices, and systems to allow optical computation and communication for flight missions. Photonic systems often perform the same functions as electronic systems, using light photons in place of electrons.

The development of photorefractive semiconductor materials has potential in cascaded optical processing systems. Researchers used a dc electric field to demonstrate net gain in beam coupling in semi-insulating gallium arsenide: the intensity of a two-dimensional optical image can be amplified using optical processing in the photorefractive semiconductor.

The CSMT is developing organic materials with applications in optical computing, communications, and data storage. Such materials can, for instance, double or triple the frequency of incident light. CSMT engineers have demonstrated materials that have frequency-doubling coefficients four times larger than any previously known; several patents have been filed.

Hypercube Computing

The Caltech Campus–JPL Hypercube project continues to provide leadership in research, development, and use of concurrent computers. JPL is adapting the Hypercube computer architecture to a fault-tolerant space computer. A study has also identified three fault-tolerant Hypercube architectures to meet performance and fault-tolerance requirements for Strategic Defense Initiative missions.

Final integration and testing of the 128-node Mark IIIfp is proceeding. It will be delivered to Caltech Campus early next year and will perform 250 to 1,500 million floating-point operations a second, far faster than any current supercomputer.

Mark IIIfp applications include the continuing work on large-scale system simulations, programs in physical modeling (astrophysics, geophysics, and plasma physics), the first use of a concurrent input/output system for data analysis, image analysis and reconstruction, and a general synthetic-aperture radar processor.

Fault-tolerant Hypercube architectures depend on rapid and sophisticated message processing. A new device called the Hyperswitch helps accomplish this processing by directing the computer to execute a message, by queuing messages, and by adaptive message routing. The Hyperswitch reduces delays in communication between Hypercube nodes and enables the Hypercube to solve entirely new classes of problems.

There is growing interest in the Hypercube: more than 550 people attended the Third Annual Hypercube Conference in Pasadena in January, and more than five companies are making Hypercube products.

Electronic Neural Networks

Artificial neural-network circuits are derived from models of the massively parallel architectures of the human brain—the many simple, decision-making cells (neurons), and the synaptic interconnections among them.

Development of novel concepts and materials to create electronic hardware that mimics the brain's networks is a major effort of the Center for Space Microelectronics Technology. This research is sponsored by NASA and Defense Department agencies. Investigators are developing a unique breed of analog memory and processing devices for parallel, high-speed, neural-network hardware.

For example, a neural-network prototype hardware system for high-speed parallel processing of analog sensor inputs is being evaluated for determining the cross-country mobility of vehicles under geographic and weather constraints. Programmable, thin-film memory elements developed at JPL are ideal for storing massive amounts of information. Finally, the recent development of analog memory devices will allow the development of neural-network algorithms that learn from experience.

Time Warp

Invention of the Hypercube at Caltech made great increases in computing speed possible—if only the machines could be programmed. So JPL computer scientists developed an operating system called Time Warp that has several applications. One of these, for the Army, uses multiprocessors in discrete event simulations. A discrete event simulation is a computer program for investigating large systems that cannot be modeled easily or tested directly.

Time Warp is an operating system for parallel-process architectures such as the Hypercube. It manages computations by distributing them among nodes that operate in parallel, so that idle nodes can operate independently and work ahead of schedule even if this means processing messages out of order. Time Warp detects messages processed in the wrong order and corrects automatically. When an object receives a message with a time stamp in its past, Time Warp reverts to a saved state of processing, removes incorrect information, and continues forward. The hardware frequently used in these applications is the Caltech Campus–JPL Mark III Hypercube. However, Time Warp has also proven successful with other multiprocessors. Simulations on the Mark III Hypercube show that with Time Warp, the 64-node processing allows 28.5 times faster processing than that possible with a single node.

Space Science Information Systems

The exploration of space involves many information systems, from those that design instruments and orchestrate them in flight to those that perform remote observations. From the days when engineers handled mere thousands of bytes of data a day, NASA now receives hundreds of millions of bytes a day. The Earth Observing System will bring terabytes of data every day from instruments that operate in many fields.

JPL has been a pioneer in applying advanced information technology to space research, data analysis, information compression and distribution, concurrent processing of image information, and systems prototyping. In particular, JPL engineers have pioneered the use of Compact Disk–Read Only Memory (CD–ROM) to archive

and distribute science data. Two disks have been produced, one that contains 800 full-resolution images from the Voyager Uranus encounter, and another that contains data from the major NASA science disciplines and the major data types—astrophysics, solar, planetary, land, and ocean.

Though improvements have already been made in methods for handling data, more must be made. JPL's Navigation Ancillary Information Facility has provided accurate and timely support for Voyager, and JPL is helping to plan observations of moving targets by the Hubble Space Telescope.

Yet another challenge is high-speed image processing. Concurrent computation systems such as the Hypercube increase power, but are still difficult to program. A Concurrent Image Processing Executive (CIPE) will provide an architecture-independent environment for images. CIPE is an improvement of about 100 times over conventional methods.

Still another important component of information systems involves helping to plan flight projects and develop the new Space Flight Operations Center (SFOC). This year the Flight Projects Office (FPO) established an Information Systems Testbed. Its initial tasks are science support for Voyager's Neptune Encounter, a map-display prototype for Mars Observer, and support of the Space Flight Operations Center.

Automation and Robotics

The field of automation and robotics is the second of JPL's major technology thrusts. The goal is to create machines intelligent enough to work largely on their own instead of having to be told everything by human operators. Space telerobot and planetary rover research are two components of JPL's automation and robotics program. Telerobots will build, service, and repair equipment in space, while planetary rovers will have a role in the unmanned exploration of planets and satellites.

Space Telerobotics

JPL is developing a laboratory telerobot testbed to support space-robotic research and development. The machine will be operational next year, blending remote control with robotic autonomy to produce a synergistic man–machine system. Initial versions exist of three subsystems: sensing and perception, manipulation and control, and run-time control.

The testbed's capabilities include machine vision to track an object and verify its location, control of robot arms, run-time task-sequence execution, and a subsystem to plan tasks and allocate resources. The system is made up of three robot arms—two to manipulate objects and one to position a stereo camera—a stereo-vision system, and two task setups—one to track a satellite and grapple it, and one to change modules in the satellite.

In the first test, the equipment tracked a 400-pound satellite mock-up that was rotating at two revolutions a minute. While software in the vision system determined the satellite's position within 0.2 of an inch twice each second, the robot arms synchronized with the satellite, grappled it, and stopped its rotation.

The second task consisted of a series of steps that involved a decision at each step. The task was to loosen a bolt under a hinged door that could be obstructed by a crank. The testbed was to make an automated search for the crank, decide whether to move it, open and hold the hinged door with one robot arm, select a tool with the second robot arm, and then engage and turn the bolt. The testbed found the crank's position to an accuracy of 0.5 degree, grasped the crank handle with clearance tolerance of 0.1 of an inch, and then moved the crank through 30 degrees.

Semiautonomous Navigation of Planetary Rovers

Astronauts sent to Mars will be preceded by roving vehicles that must move about the dusty surface and conduct complex scientific experiments. Navigation is a complex task for an automated vehicle. However, JPL scientists and engineers have recently demonstrated techniques

for navigating a robotic vehicle. In semiautonomous navigation, a human identifies destinations and uses a computer map called a terrain database to define the rover's route to its destination. The rover then uses information from its own sensors to choose a path around small obstacles that are not in the database and tracks its progress by matching data from its sensors with the terrain database.

Engineers moved a prototype rover across the arroyo adjacent to JPL and performed all the required steps. A more capable machine is being developed with more sensors, faster onboard computing, improved reasoning, and a manipulator arm.

In addition to such work in the two major Technology Thrust areas, JPL engineers made a large number of other advances during the year in a wide selection of fields.

Array Feeds to Compensate for Surface Distortion of Reflectors

Demands on satellite communications systems and scientific spacecraft are increasing, so large antennas must perform better. Reflectors are more popular than other antenna designs because they provide narrow beams with high gains at low cost. However, environmental conditions can distort the surfaces of large reflectors, thereby degrading performance.

Recent investigations show that array feeds are more cost-effective than mechanical actuators behind an antenna's surface. The array-feed approach is particularly useful where distortion varies slowly, as is typically the case with large reflectors subject to changing temperatures and gravity forces as they track spacecraft across the sky.

An experiment has demonstrated the utility of this concept. The reflector and array feed consist of 19 elements with an analog phase shifter and a variable attenuator behind each element. The new design will help to improve large antennas and it may relax requirements for surface accuracy, introducing a new direction for their design.

High-Performance Solar Array Research and Technology

In 1988, JPL progressed toward the NASA Office of Aeronautics and Space Technology (OAST) goal of demonstrating a lightweight photovoltaic array design that can provide 130 watts per kilogram. The solar array's performance represents a five-fold improvement over a conventional spacecraft array and will double the performance of an array that was tested on the space shuttle in 1984. Engineers built a light, eight-panel flexible blanket with 1,440 live, thin solar cells in circuit and 4,320 cell-mass-simulating aluminum chips. The engineers also built an ultralightweight canister and mast to deploy the stowed blanket. The new array can be used on high-powered, advanced, Earth-orbiting spacecraft and will operate at great distances from the Sun. Using advanced solar cells, the array design will provide 300 watts per kilogram.

Electrochemical Power

In the area of electrochemical power, JPL worked on a lithium-thionyl-chloride primary battery for the Centaur launch vehicle, studied lithium-titanium-disulfide batteries for the Mars Rover, pushed development of high-power batteries for the Air Force, and worked on a model for nickel-cadmium batteries with long lifetimes.

The Centaur battery work resulted in scaling-up D-size, high-rate 10-ampere-hour cells, developed by JPL, to 150-ampere-hour size. Lithium cells can save 240 pounds per launch and will improve the performance of expendable launch vehicles.

Work on rechargeable lithium batteries is an effort to understand their reactions and limitations. Lithium-titanium-disulfide cells are capable of 100 watt-hours per kilogram and have a life of up to five years in activated storage. The cells may be used in Mars Rover.

Other work involves development of a sealed, bipolar, lead-acid battery. Bipolar construction provides a current path directly through a series of cells, rather than through bus bars and external wiring. Bipolar design gives high current flow with minimum resistance. Power should be 5 kilowatts per kilogram, compared to 0.1 kilowatt per kilogram for a typical battery.

A New Workstation for Monitoring Spacecraft Telemetry

Several space missions are due in the next decade, and JPL must perform ground operations for all of them simultaneously. The project manager of each mission usually prefers a ground operations crew that is trained for each specific mission. This, however, would require a tremendous growth in workforce. To limit such growth, JPL is redefining ground operations and using graphic displays.

Without graphics technology, monitoring spacecraft is a tedious operation that requires many people. Printed data provide no understanding to inexperienced observers, and each operator typically concentrates on one subsystem in a single mission. In response, JPL has developed a prototype system that can process and graphically display engineering telemetry. Operators can now monitor the statuses of several subsystems simultaneously, understanding any one at a glance.

Thermal Power Conversion

Silicon and germanium are semiconductors whose alloys are used in radioisotope thermoelectric generators to convert heat to electric energy. Silicon germanium has several benefits as a source of power: no moving parts, long life, and compact size. By incorporating multiple instead of single dopants into the alloys, conversion efficiency improves about 30 percent. Another 30 to 50 percent improvement may be possible.

Alkali Metal Thermoelectric Converter

The Alkali Metal Thermoelectric Converter is a direct thermal-to-electric conversion device that will convert heat to electricity at 20 to 25 percent efficiency. By coupling the converter to a nuclear heat source, power-to-mass ratios can be increased over the state-of-the-art static power sources used in planetary probes today. Electrode compositions with the performance that space missions require have been found. This, along with an analytical model of electrode mechanisms, increases the confidence that long-term, high-efficiency performance can be achieved.

High-performance Rhenium Rocket Engine

JPL has completed a study of a high-performance, long-life, bipropellant rocket engine that demonstrated the feasibility of an improved engine using monomethyl hydrazine/nitrogen tetroxide.

Analysis of the Comet Rendezvous Asteroid Flyby (CRAF) mission showed that using a high-performance engine in place of a conventional one would cut the spacecraft's weight by more than 600 kilograms. This would make it possible to launch with a full complement of science instruments on a Titan IV launch vehicle. Without an improved engine, the expected science return would be much less.

The improved performance was achieved using materials that permit higher operating temperatures, thus providing greater rocket-nozzle exit velocities and greater specific impulse. Rhenium was used as the high-temperature structural material. An iridium coating prevented corrosion.

JPL first explored high-temperature rocket engines in the 1970s. In 1982, research was done to adapt the rhenium engine as a hydrogen/oxygen thruster for the space station. When it was clear that the CRAF spacecraft could not carry a full payload with its existing engine, the project

sponsored a program to adapt the rhenium concept to a monomethyl hydrazine/nitrogen tetroxide engine.

Advances in Xenon Ion Engines

Ion engines impart thrust to a spacecraft when ions created in a plasma are accelerated out of the engine at velocities approaching 50,000 meters per second. The high exit velocity allows ambitious planetary missions to have shorter trip times and use less propellant than with chemical propulsion. For primary propulsion, ion engines must have lifetimes of more than 10,000 hours. The life-limiting factor is erosion of the plasma-chamber surfaces when high-velocity ions strike them and remove material.

JPL studied the erosion characteristics of mercury-ion engines and modified the engines to operate on xenon by using a 10-kilowatt xenon ion-propulsion module. Erosion rates of some components appear to be much greater than those for mercury engines. As a result, engineers are studying techniques to increase xenon-ion-engine lifetime. Early data indicate that adding nitrogen reduces erosion by a factor of four or more. Completion of tests may solve the remaining technical issues.

Precision Segmented Reflectors

NASA's Precision Segmented Reflectors (PSR) program is an effort to develop technologies that will support missions in astrophysics and optical communications. The missions require large, multisegmented, lightweight reflectors for large telescopes and optical receivers. Since their dimensions are expected to be larger than those of the shuttle cargo bay, the reflectors will have to be erected in orbit.

The PSR program addresses three areas: development of one- to two-meter lightweight panels that can be assembled into a large reflector; a concept for high-precision lightweight structures to support the panels; and controls to maintain a precisely aligned surface despite temperatures and aging.

Large Deployable Reflector

The Large Deployable Reflector (LDR) is a concept for an Earth-orbiting, submillimeter/far-infrared, astronomical observatory. The Space Science Board of the National Research Council recommended the LDR as "one of the highest priority missions for the U.S. astronomical community." The concept is a diffraction-limited, 20-meter-aperture, reflecting telescope that will operate in wavelengths between 30 and 1,000 micrometers, a region that has remained unexplored because the Earth's atmosphere is almost completely opaque at these wavelengths. The reflector's sensitivity and angular resolution would allow detailed studies of the formation of stars and planetary systems, the nature of infrared galaxies, and the birth of galaxies and clusters of galaxies.

JPL recognizes that a submillimeter astrophysics program is needed to define the requirements of the Large Deployable Reflector and to help direct the technology. To that end, JPL is involved in several programs that would precede the LDR. These include the Kuiper Airborne Observatory aircraft, the Large Aperture Balloon, and the Small Explorer and Submillimeter Explorer spacecraft programs and proposals.

Mobile Satellite Experiment

JPL is developing the technology for communicating between a moving automobile or truck and a fixed ground station through a geostationary satellite. The system should augment cellular telephones by providing voice and data service to remote areas.

Engineers tested models of ground terminals in the field. The terminal provides data transmis-

sion and digitized voice over a narrow channel. Low-cost antennas were also field-tested near Boulder, Colorado, using a transponder on a 1,000-foot tower to simulate a satellite.

To help spread these developments throughout industry, JPL sponsored a conference on mobile satellite communications attended by nearly 400 engineers and scientists. More than 70 papers addressed the issues of antennas, speech compression, modulation, coding, propagation, network control, system architecture, spacecraft payload design, and governmental regulation.

Telecommunications Systems

The Deep Space Network (DSN) is NASA's worldwide system for transmitting instructions to spacecraft and receiving the data that they collect in deep space and Earth orbit. JPL manages the network, which has antennas clustered at three sites: Goldstone Dry Lake in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. The three locations allow antennas to track spacecraft anywhere in the solar system. The Network Control Center and its supporting facilities are at JPL. Satellite and ground communications link all locations.

Each site is equipped with four large antennas from 26 to 70 meters in diameter. During encounters, antennas at each complex can be arrayed to increase data return. The antennas can also be teamed for scientific investigations, using techniques such as Very Long Baseline Interferometry (VLBI), in which simultaneous measurements made by two or more widely spaced antennas can work as if one giant antenna spanned the distance between them. The technique, originated by radio astronomers, is used for precise geodetic measurements.

Tracking and Data Acquisition

Arraying Demonstration with Voyager

The Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) in Socorro, New Mexico, was arrayed for the first time with the Goldstone 70-meter station on June 29. Twenty-three New Mexico antennas were arrayed and then in turn were arrayed through satellite with the Goldstone antenna.

When all 27 antennas are instrumented and arrayed with the Goldstone antenna, the VLA will double the DSN's ability to receive high-rate data—Voyager will achieve the maximum science return during its Neptune encounter.

Reimbursable Launch Support by the Deep Space Network

The DSN provides reimbursable launch support to several non-NASA agencies such as Japan's National Space Development Agency and its Institute of Space and Astronautical Science, the French Centre National D'Etudes Spatiales, the German Space Operations Center, and the European Space Agency.

In 1988, the DSN supported TV-SAT for the Germans, CS-3a and CS-3b for the Japanese, and Telecom 1-C and TDF-1 for the French. These reimbursable launches allow the DSN to train crews and to maintain proficiency. Such training will be essential for JPL launches, which will resume next year.

Completion of the 70-Meter-Antenna Upgrade

The upgrade of the 64-meter antenna at Goldstone, which started in October 1987, was completed in May. All the large-aperture antennas have now been upgraded to a 70-meter diameter for Voyager's Neptune encounter.

The latest technology produced panels whose surfaces vary less than 0.1 millimeter. Microwave holography was used to set the panels so that overall surface variation is less than 0.5 millimeter. The 70-meter antennas also use specially shaped reflector surfaces that reduce diameter requirements. Had the antenna surfaces been the usual paraboloid shape, their diameter would have had to be 82 meters, an additional 12 meters in diameter. The overall improvement of the antennas is about 60 percent.

X-Band Uplink Capability Added to 34-Meter Net

To support spacecraft that can receive X-band transmission, such as Galileo and Magellan, 20-kilowatt X-band transmitters were added to one 34-meter station at Madrid and one at Canberra. A third will be added at Goldstone. The modifications allow simultaneous transmission and reception at X-band. This equipment may be able to measure gravitational waves as they propagate through space by detecting perturbations in the phase of the X-band signal from the spacecraft.

Magellan Era Modifications

New computer equipment and programs have been installed in the DSN so that it can receive and process data at rates up to half a megabit (500,000 bits) per second. The capacity is needed for Magellan, Mars Observer, and highly elliptical near-Earth flights.

Very Long Baseline Interferometry

Very Long Baseline Interferometry (VLBI) is one of the most reliable methods for measuring locations on Earth and for navigating spacecraft. Measurements are made with a few large antennas that are either at fixed sites or can be moved only at considerable expense. However, receivers that process signals for Global Positioning System (GPS) satellites are relatively inexpensive and portable. If accuracy compares with interferometric methods, it will allow scientists to monitor geophysically active regions.

JPL has been involved in experiments to develop analysis techniques and provide benchmark measurements of stations for geophysical research. One interesting area is the San Andreas Fault in California. The Earth's crust is deforming

across the fault at a rate of several centimeters a year. Thus, space-based measurements may let scientists distinguish between competing geophysical models of the region. California, which has been monitored for almost a decade by VLBI, provides a good testbed for studying GPS-based geodesy.

A Global Reference Frame With 10-Nanoradian Accuracy

Analysis of seven years of VLBI data has produced a catalog of radio-source positions with an average accuracy of 10 nanoradians, which is about the angle subtended by a dime in New York as seen from Chicago or about eight kilometers at the distance of Jupiter. The old catalog had an average accuracy of 35 nanoradians. The radio sources are used as benchmarks against which to navigate; the new catalog will be used to navigate spacecraft such as Galileo and Magellan.

Very Long Baseline Interferometry Observations From Space

New observations in another interferometry experiment have yielded information about quasars and galaxies. A team led by JPL used the Tracking and Data Relay Satellite antenna in space and large antennas in Australia and Japan to produce the longest baselines ever achieved with radio interferometry. The team made observations in February and March and detected 11 quasars and radio galaxies. Data are still being reduced. The network used the 70-meter Australian antenna in all observations, along with the Japanese Institute for Space and Astronautical Sciences' 64-meter antenna at Usuda (about 120 kilometers from Tokyo), and the 45-meter antenna of the Nobeyama Radio Observatory (about 100 kilometers from Tokyo).

Radar Support

Goldstone Solar System Radar

JPL radar astronomers have concluded from Goldstone radar data that iron pyrite or a similar compound has been exposed recently on the surface of Venus by meteor impacts or volcanic eruptions. Radar on the Pioneer Venus orbiter apparently saw similar material in the mountains, but the DSN observations were of equatorial plains, which are much hotter. Pyrite should break down even more quickly in hot, corrosive, low-lying areas than in the highlands. However, the time needed to weather away iron pyrite requires more research, and so the material can be only roughly categorized as recent.

The 70-meter Goldstone antenna was combined with the Very Large Array (VLA) for radar studies of Saturn's rings using Goldstone's X-band transmitter. The Caltech Division of Planetary Sciences participated in the experiments, which detected strong echoes in both operating modes. Twenty-three of the 27 VLA antennas were equipped for X-band. Thus, 253 baselines were formed. The data permit two-dimensional mapping of the backscattered signal across the sky.

The summer of 1988 also saw observations of the last close approach of Venus before Magellan's launch, yearly observations of Mercury during its close approach (jointly conducted with the Arecibo Radio Observatory in Puerto Rico), and the best opportunity to observe Mars until the 21st Century. This year's Mars opposition was the closest in 17 years. In mid-September, the first joint VLA observations of Mars were carried out. Other firsts included radar observations of Phobos (a Mars satellite) and ranging observations of the Earth-approaching asteroid 1980 PA.

Alaskan Radar-Satellite Receiving Station

JPL, NASA, and the University of Alaska installed a 10-meter antenna on the eight-story Geophysical Institute at the University's Fairbanks campus. The antenna, operated by the University, will acquire data from the European Space Agency's ERS-1, Japan's JERS-1, and Canada's Radarsat satellites. These data will be used to study ice dynamics in the north polar regions.

Ground Telecommunications Technology

A Tool for Deep Space Microwave Communication

On October 10, a groundbreaking ceremony marked the beginning of construction for a 34-meter antenna at the Goldstone Venus research and development station. The antenna's design is a beam-waveguide (i.e., Coudé focus), a significant departure from traditional Cassegrain antenna designs. In a beam-waveguide antenna, the energy collected by the main surface is guided by smaller curved and flat mirrors to a large room below the antenna. Such an antenna increases the capability to transmit and receive at frequencies that are not used now. The new design has several innovations. The antenna must perform as well as the 34-meter subnet with respect to deformations by gravity and wind. Existing 34-meter antennas can be upgraded to beam-waveguide using technology developed for the new antenna. These new features could be incorporated in future DSN antennas.

The new antenna will demonstrate both the 32-gigahertz frequency range (Ka-band) for communications and navigation as well as the benefits of the beam-waveguide design. The advantages could be exploited to design smaller, lighter spacecraft.

Improved Coding for Galileo

The Galileo telemetry link became the focus of intense activity in 1988. The new launch date causes reduced telemetry margins for encounters. On the other hand, the launch delay allowed the DSN to seek countervailing enhancements. One is a lengthening of Galileo's convolutional code in order to work closer to theoretical limits in combatting the noise that affects the signal received from Jupiter.

For given parameters, there are many possible codes. JPL researchers found a convolutional code that improves performance 25 percent and can be used by Galileo as is, with just the addition of the encoder. JPL engineers also designed the decoder that the DSN will need. The encoder was put on the spacecraft as a switchable, experimental alternative to a standard encoder. If not for improvements, the new decoder would have been 256 times as complex as the old.

Advanced Receiver Tracks Voyager 2 Near Solar Conjunction

In December 1987, as Voyager 2 began to disappear behind the Sun, JPL's Advanced Receiver tracked the spacecraft at low Sun–Earth–probe angles. The receiver tracked Voyager from 11 degrees to within less than 1 degree from the Sun.

The experiment showed that the DSN could use narrower loops in its receivers when spacecraft are on opposite sides of the Sun from Earth or when they explore near the Sun. The work also provided an opportunity to study the effects of the Sun's corona on radio transmissions and to evaluate a way of improving carrier loop bandwidths, developed for use with the Advanced Receiver.

Lasers for Spaceborne Applications

There is an increasing demand for low-power lasers for satellite-to-satellite and satellite-to-ground optical communications or remote sensing. A compact laser module was designed, built, and tested at JPL. The module is a neodymium:yttrium aluminum-garnet solid-state laser, optically pumped with a pair of diode-laser arrays. The output power is 130 megawatts with about seven percent efficiency. The laser performed well even after it went through the vibration and temperature conditions experienced during a shuttle launch.

Applications Projects

JPL applies its capabilities for advanced systems development along with its broad array of technology strengths to projects of national importance outside NASA. Sponsors range from organizations in the Defense Department (DoD) to agencies such as the Federal Aviation Administration (FAA) and the Department of Energy (DoE).

The year was notable for several milestones, including accelerated development and delivery of a flight instrument for a Strategic Defense Initiative satellite, turnover of two completed command and control systems to the Air Force, and completion of new analysis and training software for the Defense Department's Joint Warfare Center.

ASAS/ENSCE Project

The All-Source Analysis System/Enemy Situation Correlation Element (ASAS/ENSCE) will field a baseline data processing system for Army and Air Force tactical intelligence in the early 1990s. The system uses computer workstations in field modules. The computers receive large quantities of intelligence data, then analyze, prioritize, and process the data for battlefield commanders. Several prototype workstations have been delivered to the Army and used in field exercises with considerable success. The software and hardware for configuration of the overall system, with limited capability, were developed by JPL and its subcontractors and delivered to a system contractor for integration and delivery to the Army in 1989.

SP-100 Project

JPL manages the SP-100 Project under sponsorship of the Department of Energy (DoE), Defense Department, and NASA. SP-100 is developing a ground-test model of a nuclear reactor power system for uses in space including deep-space-exploration missions.

The project passed a milestone in 1988—completion of the Reference Flight System designed for a 100-kilowatt version. Its features include a fast-neutron reactor cooled by liquid lithium, a heat-transport subsystem using thermoelectromagnetic pumps, a thermoelectric power-conversion subsystem, a heat-rejection subsystem, and shielding, control, and structural elements.

Among the design challenges in the development of SP-100 are the state-of-the-art thermoelectric-conversion devices (miniature thermoelectric couples) that will produce, in the same volume, about 25 times the power of similar hardware for the radioisotope thermoelectric generator used on Galileo.

Voice Switching and Control System

The Voice Switching and Control System is a large, state-of-the-art, computer-controlled telephone switching system being developed for the Federal Aviation Administration (FAA). Two elements are being developed: one by American Telephone and Telegraph (AT&T) and one by Harris Corporation. Meanwhile, JPL is developing hardware and software that will allow the FAA to test these new air-to-ground and ground-to-ground systems.

JPL's Traffic Simulation Unit provides simulated voice traffic and measures traffic timing and audio quality. The unit permits the system to be loaded up to 200 percent of peak busy-minute loads.

In 1988, JPL completed the design and development of the traffic simulation unit and tested its segments. System integration and test will take place in 1989 and the unit will be delivered during the second quarter.

Analysis and Training System

JPL has developed a computer-based system that simulates large-scale land and air combat and battlefield-support activities to help train military commanders and their staffs to make real-time battle-management decisions. The name, Joint Exercise Support System, reflects its multiservice application. It is an improvement over old methods, which used map boards and an elaborate rule book. The new system has reduced costs and raised training effectiveness for the joint military services battle-command training.

Many improvements to the system were incorporated in 1988. Now, an exercise can be split geographically and then coordinated by connecting computer systems via satellite. Prerelease versions of the new software drove two major joint command exercises that involved thousands of military personnel. The second software release was delivered to the Joint Warfare Center in December.

Real-Time Weather Processor

The Real-Time Weather Processor project will provide integration and distribution of weather information directly to air traffic controllers. The project is sponsored by the FAA for its National Airspace System Plan.

The prototype should be delivered to the FAA Technical Center late next year. The Administration plans a production contract in 1992.

Ultraviolet Imaging System for the Delta Star Flight Program

In March 1988, JPL agreed to build an ultraviolet imaging camera for the Strategic Defense Initiative Organization (SDIO) Delta Star satellite. The camera was delivered to the Applied Physics Laboratory of Johns Hopkins University on July 21.

The camera has an all-reflecting telescope with a 6-inch aperture and a focal length of 87.4 inches. A filter wheel allows selection of any of five wavebands, all invisible to the human eye. A low-light-level image intensifier and automatic exposure control can be directed by ground commands. The instrument was to arrive at Cape Canaveral in late November. Delta Star is to be launched in January 1989.

Command and Control Automation

The Command and Control Automation project delivered two systems to the Air Force Military Airlift Command: Wing Integration for Global Support (WINGS) and a Global Decision Support System. WINGS is a PC-based information processing and display system at McChord Air Force Base in Seattle, Washington. It is the keystone for controlling military transportation in the Pacific.

The Global Decision Support System is a worldwide information processing and display setup for the Military Airlift Command's top three command echelons. It supports operational nodes in Washington, D.C., New Jersey, Florida, Missouri, California, Hawaii, and West Germany.

Institutional Activities

Research and development costs for the fiscal year ending in September were $1.035 billion, a 16 percent increase over 1987. Costs for NASA-funded activities rose 17 percent to $698 million. Costs for non-NASA activities were $337 million, an increase of 14 percent. The workforce increased to 5,736 from 5,465 in 1987 and 5,393 in 1986.

Procurement obligations during the fiscal year totaled $656 million, 7 percent higher than in 1987. This included $621 million to business firms, of which $251 million went to small businesses and $40 million to minority-owned businesses.

During the year, JPL contractors completed three major new facilities: the 98,000-square-foot Earth and Space Science Laboratory, the 38,000-square-foot Microdevices Laboratory, and the 78,000-square-foot Engineering Support Building. A third cafeteria also opened.

In October, NASA and Caltech renewed the prime contract for JPL for an additional five years.

Director's Discretionary Fund

The Director's Discretionary Fund is the primary resource for support of innovative and seed efforts that cannot receive conventional task-order funding. The fund level is now $3 million a year.

In 1988, the fund initiated 34 new research tasks and extended the objectives of and awarded more funds to nine ongoing tasks. Eligible proposals cover a range of sciences and technologies, including the following areas of special emphasis: advanced microelectronics, automation and robotics, infrared- and submillimeter-wavelength technology, and detection of planets beyond the solar system.

The fund recognizes important mutual benefits from collaboration with faculty and students at Caltech and other universities, so cooperation is specifically encouraged. Fifteen tasks funded in 1988 involved university faculty collaborators from the United States and foreign countries.

President's Fund

The Caltech President's Fund is a second source of discretionary funding at JPL. The fund, which contains $1 million a year, comes from Caltech and NASA on a dollar-for-dollar matching basis and is administered by Caltech. Objectives of the President's Fund are to encourage interest and participation in JPL activities by university faculty and students and to give JPL staff members an opportunity to associate with research workers from universities. In 1988, the President's Fund provided resources for 27 new collaborative tasks.

NASA Honor Awards

NASA Honor Awards recognize outstanding individual and team efforts. In 1987, NASA rescheduled the selection of Honor Awards. Awards presented this year recognized people nominated in 1987. Twenty-three JPL individuals, one from the University of Arizona, and eight groups won awards in 1987.

NASA Outstanding Leadership Medal:

- Robert G. Forney

NASA Exceptional Scientific Achievement Medal:

- Bradford A. Smith (University of Arizona)
- Richard J. Terrile

NASA Exceptional Engineering Achievement Medal:

- Roger E. Diehl
- John Lambe
- Robert F. Rice

Exceptional Service Medal:

- Thomas J. Bicknell
- William T. Callaghan
- Edward F. Cuddihy
- John C. Curlander
- Daniel D. Elleman
- Richard R. Green
- Wesley T. Huntress, Jr.
- Martin H. Leipold
- Gerald S. Levy
- Ralph Lutwack
- Carol L. Miller
- William E. Rains
- Tamara S. Rimmer
- R. Stephen Saunders
- John A. Scott-Monck
- Mahadeva P. Sinha
- R. Rhoads Stephenson
- J. Brooks Thomas

NASA Group Achievement Award:

- Advanced Digital Synthetic Aperture Radar Processor Development Teams
- Central Engineering Building Project Management Team
- Distributed Management Information and Control System Development Team
- Information Systems Standards Development Team
- Joint Theater Level Simulation Development Team
- Photovoltaic Projects Personnel
- Space Station Facility Lease Team
- Tracking and Data Relay Satellite Very Long Baseline Interferometry Team

Patents and Technology Utilization

In 1988, the Office of Patents and Technology Utilization (OPTU) prepared, evaluated, and forwarded to NASA reports on 239 inventions and technical innovations resulting from work at JPL. The office answered 36,692 requests from industry and the public for technical information on JPL inventions and innovations published in NASA's monthly, *Tech Briefs*. This year, *Tech Briefs* published 163 papers from JPL, 31 percent of the NASA-wide total. The U.S. Patent Office issued 35 patents to Caltech and NASA on JPL inventions.

NASA made a major award this year of $3,000 to Richard L. Sydnor and John W. MacConnell (shared equally) for their Ultra Stable Frequency Distribution System. Another 439 JPL employees received minimum patent awards ($250 to $500), nominal patent awards ($501 to $999), and *Tech Brief* awards ($150). The total amount of these awards came to $81,700.

Senior Research Scientists and Engineers

The position of Senior Research Scientist or Senior Research Engineer at JPL provides special recognition of outstanding individual achievement. Appointees are leaders in their fields who have been recommended in review by their peers. The following outstanding researchers, active participants in programs that are key to the research and institutional goals of JPL, earned Senior Research appointments this year:

David Halpern
Ocean Sciences
Martha S. Hanner
Comets and Interplanetary Dust
Robert T. Menzies
Laser Remote Sensing

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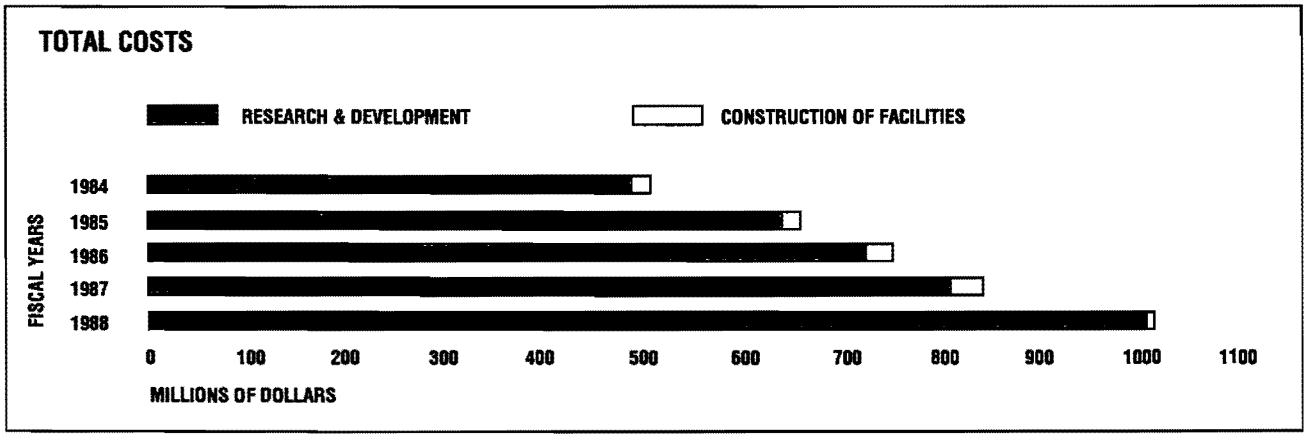

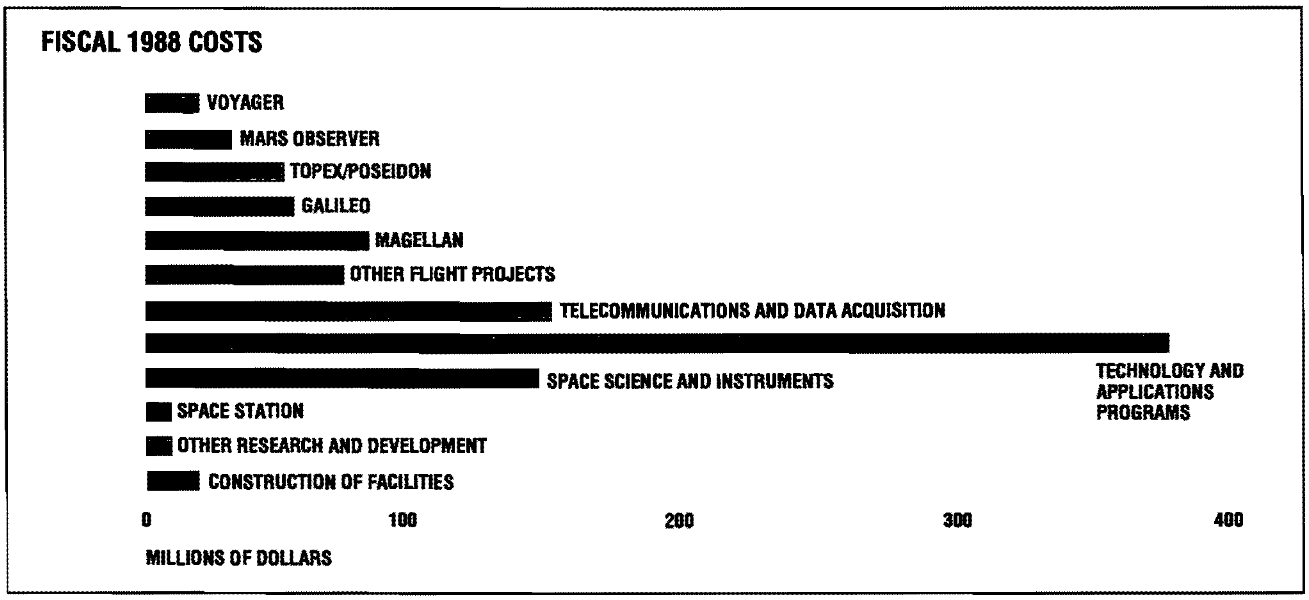

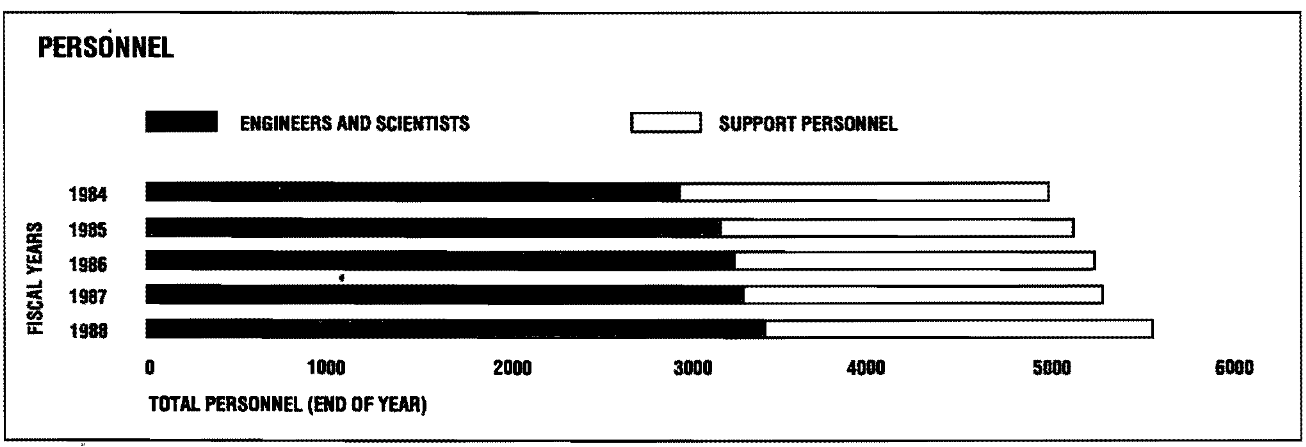

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